Novel Beam Manipulation Techniques for Fermilab Run II and Beyond

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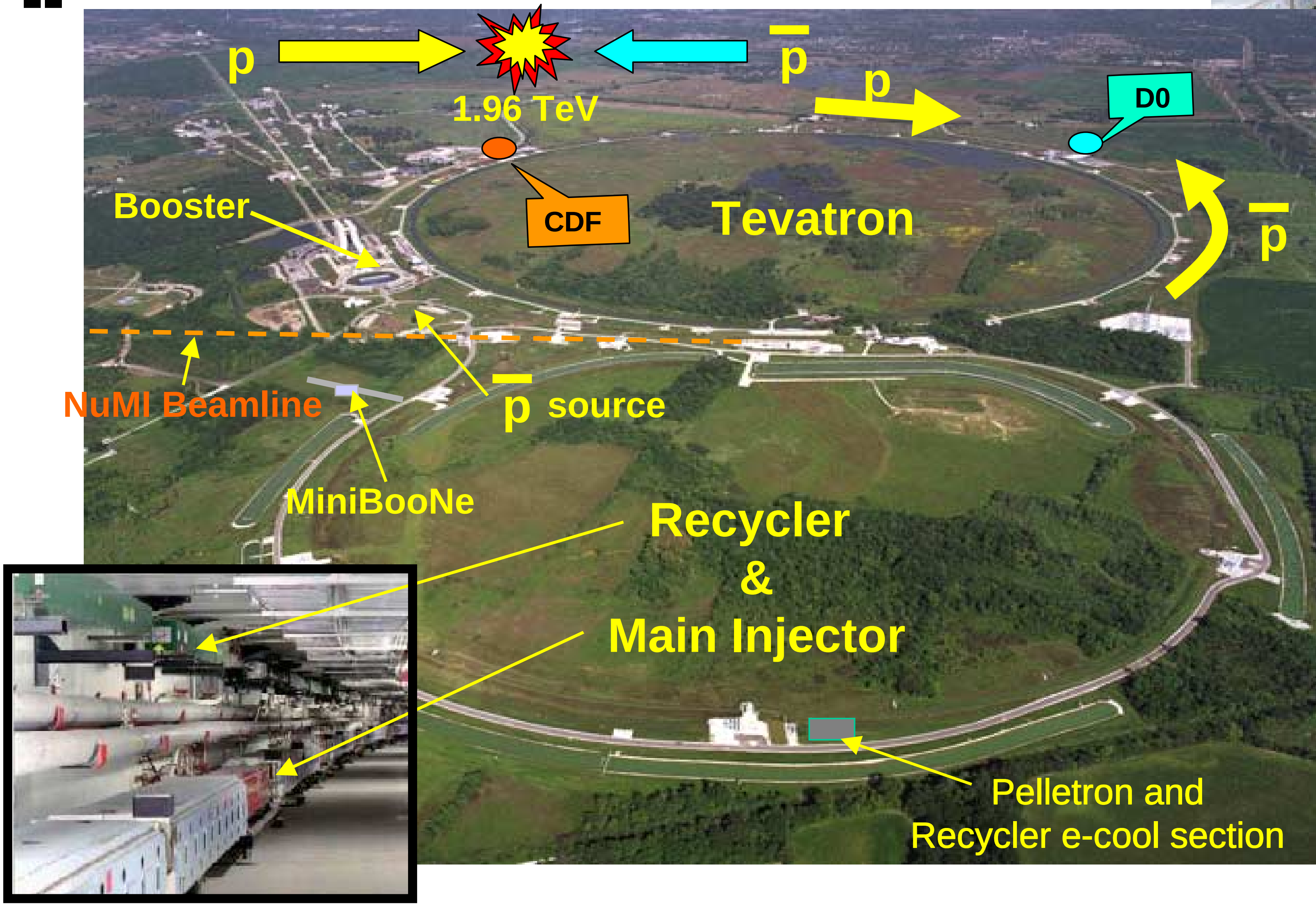
World's Pre-eminent HEP Laboratory



Luminosity

- Peak Luminosity Goals:
  - Design → 2.7×10^{32} cm^{-2}sec^{-1} (~3 over current)
  - Base → 1.6×10^{32} cm^{-2}sec^{-1} (~1.6 over current)

$$L = \frac{3\gamma f_0}{\pi\beta^*}(BN_{\bar{p}})\left[\frac{N_p}{\varepsilon_p}\right]\frac{H(\beta^*,\theta_{x,y},\varepsilon_{p,\bar{p}},\sigma^L_{p,\bar{p}})}{(1+\varepsilon_{\bar{p}}/\varepsilon_p)}$$

- Primary factors
  - Number of antiprotons: BN_{pbar}
    ←**major contributor to luminosity Upgrade**
  - Proton beam brightness: (N_p/ε_p)
    - constrained by the limit on antiproton beam-beam tune shift
    - $\varepsilon_p/(\varepsilon_p+\varepsilon_{pbar})$ **≤ 1**
  - Hourglass factor *H* **≤ 1**
- ∫L.dt Goals (By FY09): Design → 8.5 fb^{-1}; Base → 4.4 fb^{-1}

Collider Performance

Comparison between FY03 and FY04
&
Final Goal

	FY03	FY04	Gain	Goal
Peak Luminosity ($x10^{30}/cm^2/sec$)	49	107 **Goal:81**	2.1	275
Number of p and pbar Bunches	36	36		36
Proton Bunch Intensity @ collision ($x10^9$)	237	246	1.05	270
Pbar Bunch Intensity @ collision ($x10^9$)	22	43	1.95	137
Weekly Integrated Luminosity (pb^{-1})	9.7	18.6	1.92	47
Total Integral Luminosity (fb^{-1})	0.236	0.343 **Goal:300**	1.45	4.4 Base 8.5 Design.

Principal Elements of Upgrades

1. Collider Run II

- Protons on pbar target and Related Upgrades
  - Slip-stacking ← Novel Technique **3**
  - Pbar production target ←Beam sweeping ← Novel Technique
  - Main Injector Dampers
  - Bright pbar and proton bunches for collider shots ← Novel Technique **2**
- Pbar Stacking and Cooling
  - Accumulator Stack-tail Cooling
  - Recycler- stack, Cool and Un-stack ← Novel Technique **1**
  - Electron Cooling of pbars ← Novel Technique
- Tevatron
  - Helix improvements
  - Alignment
  - Instrumentation and BPM upgrades
- Anti-proton Acceptance

2. Neutrino Program and Fixed Target Experiments

- Future Proton Beam ← Novel Technique **4**

Novel Beam Manipulation Techniques for Collider Run II and other HEP Experiments

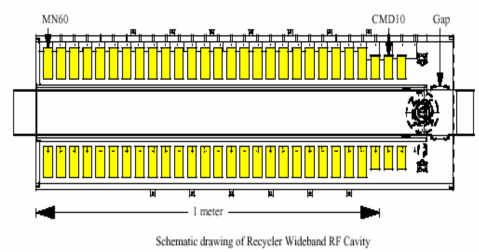
RF Cavities in the Main Injector and the Recycler Ring

MI 53MHz RF cavity

MI 2.5MHz RF cavity
(Coalescing RF cavity)

MI Damper RF cavity
(Broad Band Cavities)

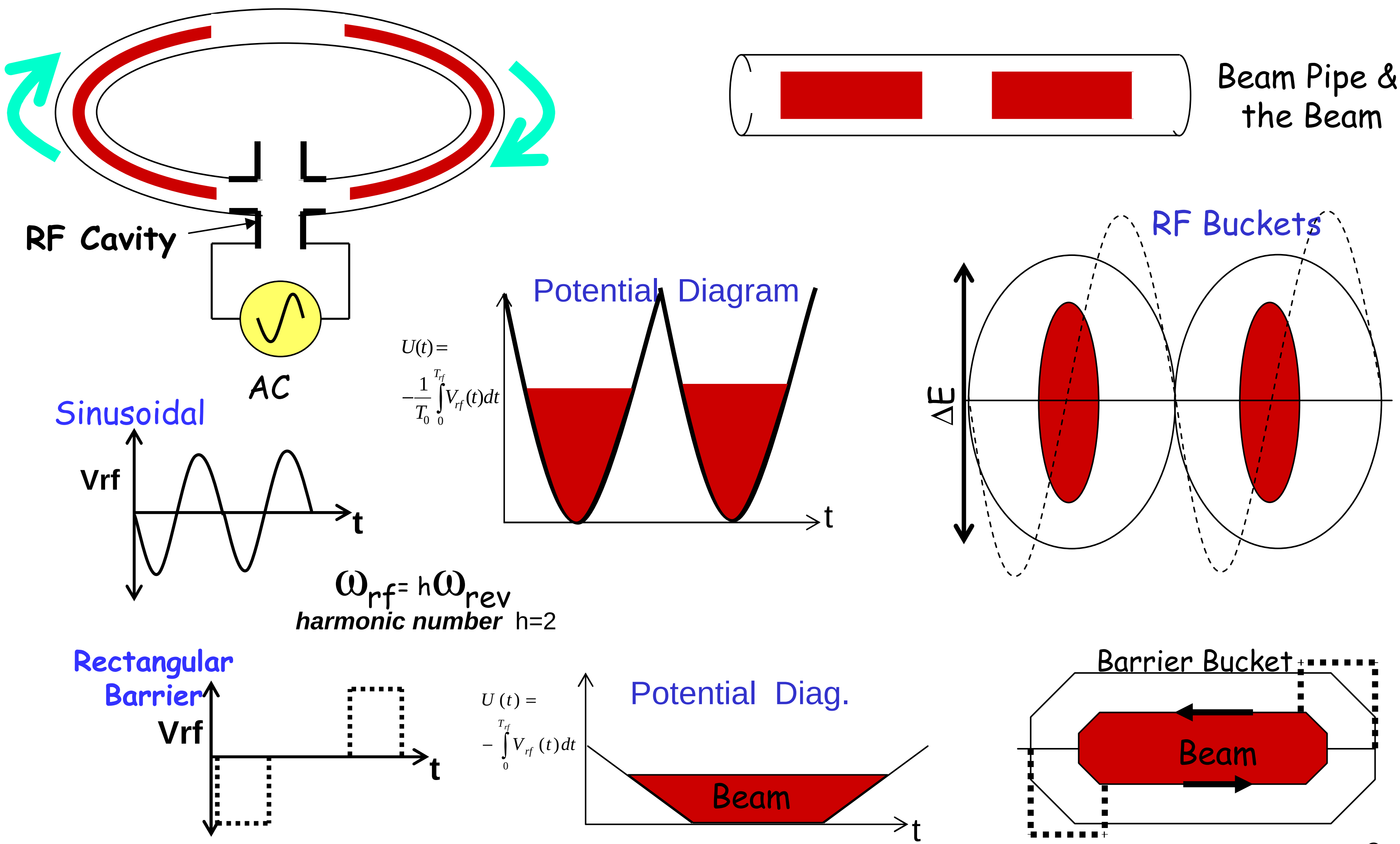
Finemet MI Damper RF cavity
(Broad Band Cavity)



Recycler RF cavity
(Broad Band Cavities)

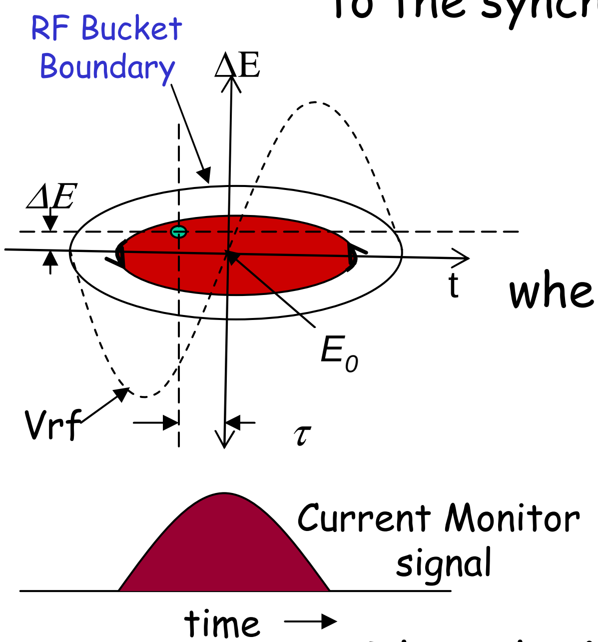
Basics of an RF Bucket

Bunched Beam with Energy $E_0 \pm \Delta E$



Equations of Motion & General Hamiltonian

The motion of a particle in a *synchrotron* with energy ΔE relative to the synchronous particle of energy E_0 is



$$\frac{d\tau}{dt} = -\eta \frac{2\pi\Delta E}{T_0\beta^2 E_0} \quad \& \quad \frac{d(\Delta E)}{dt} = \frac{eV(\tau)}{T_0}$$

where, η is phase slip factor,
T_0 = beam circulation period,
τ is the time difference between the arrival of this particle and that of a synchronous particle at the center of the rf bucket.

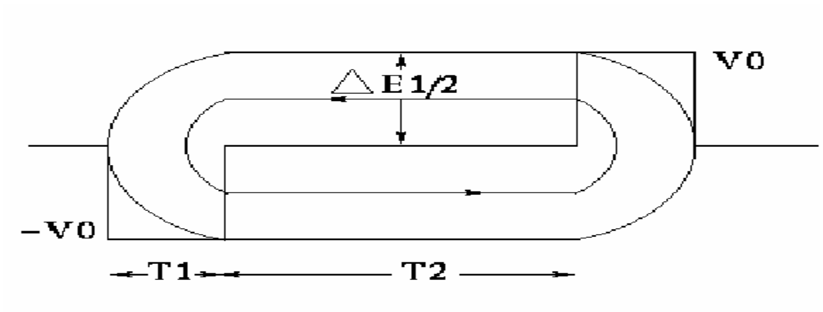
Then the **Hamiltonian** for synchrotron motion of a particle is

$$H(\tau, \Delta E) = -\frac{2\pi\eta}{T_0\beta^2 E_0}\Delta E^2 - \frac{1}{T_0}\int_0^{\tau} V(t)dt$$

for general Voltage wave form

Ref: S. Y. Lee, *Accelerator Physics*, (World Scientific, Singapore, 1999)

Properties of Barrier Buckets



Bucket height :

$$\Delta E_b = 2\sqrt{\frac{2\beta^2 E_0}{|\eta|}\frac{\int_0^{T_1} eV_{rf}(t)\,dt}{T_0}}$$

Synchrotron Period :

$$T_s = 2\frac{T_2}{|\eta|}\left[\frac{\beta^2 E_0}{\left|\Delta \hat{E}\right|}\right] + 4\frac{\left|\Delta \hat{E}\right|}{eV_0}T_0$$

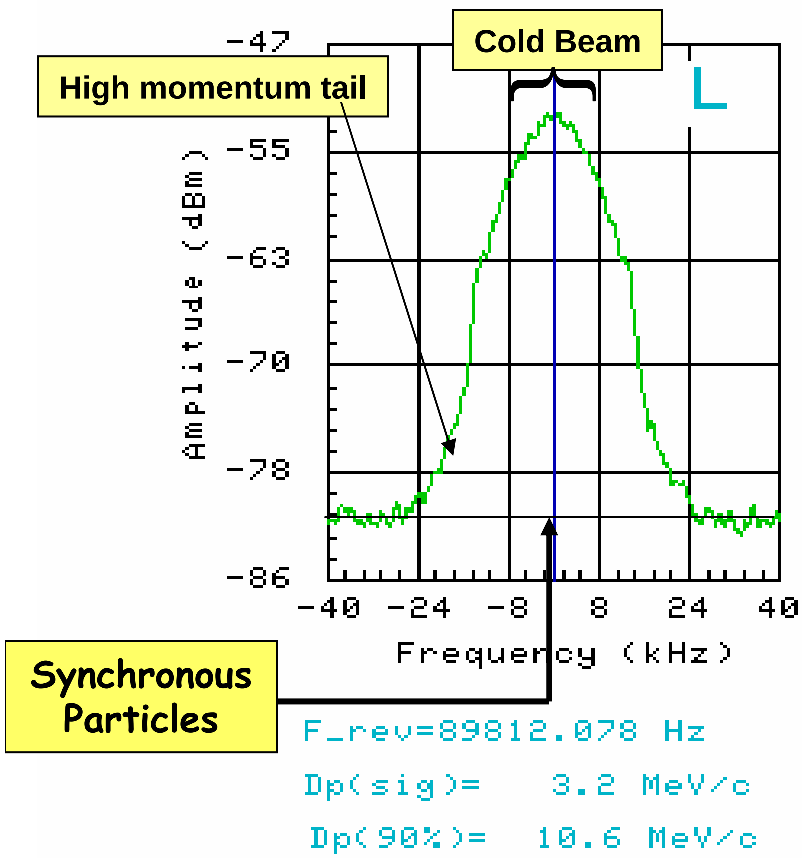
Bucket area :

$$\varepsilon_l = T_2 \Delta E_b + \frac{8\pi|\eta|}{3\omega_o \beta^2 E_o eV_{rf}}\left[\frac{\Delta E_b}{2}\right]^3$$

- η is phase slip factor,
- E_o is synchronous energy,
- ω_o=2p f_{rev} with f_{rev}= beam circulation frequency.

Momentum Mining

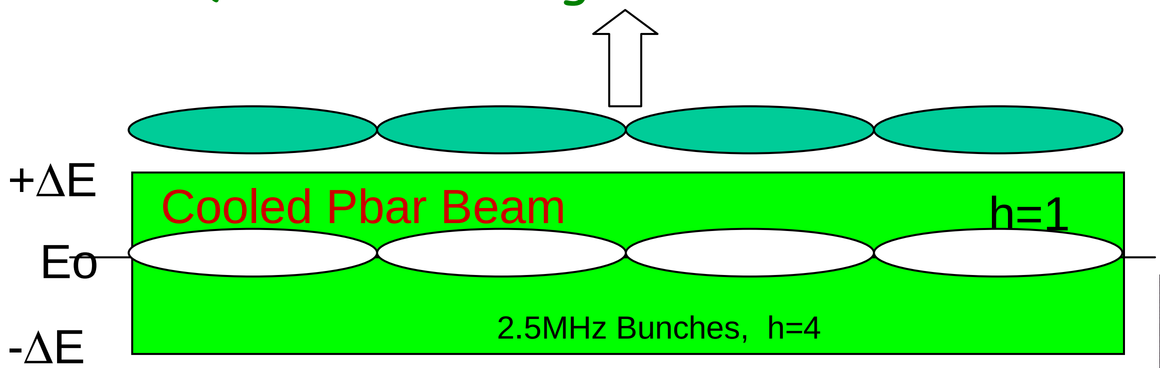
Frequency (Energy) Spectrum of the Beam

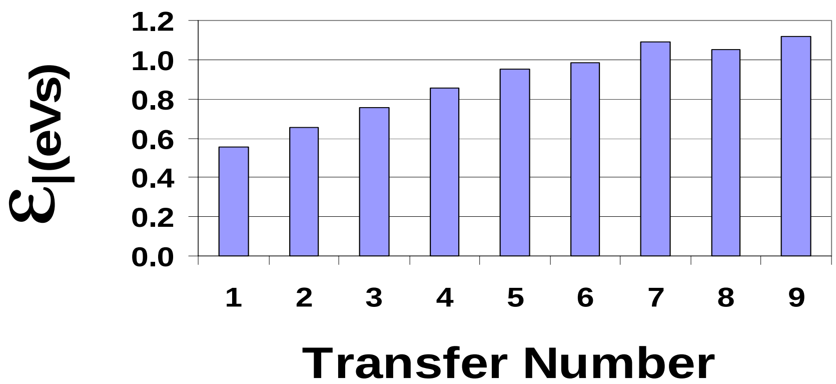


Is it possible to isolate the cold beam from the high momentum tail of a beam distribution without emittance growth and to selectively use the cold beam and cool the leftover hot beam?

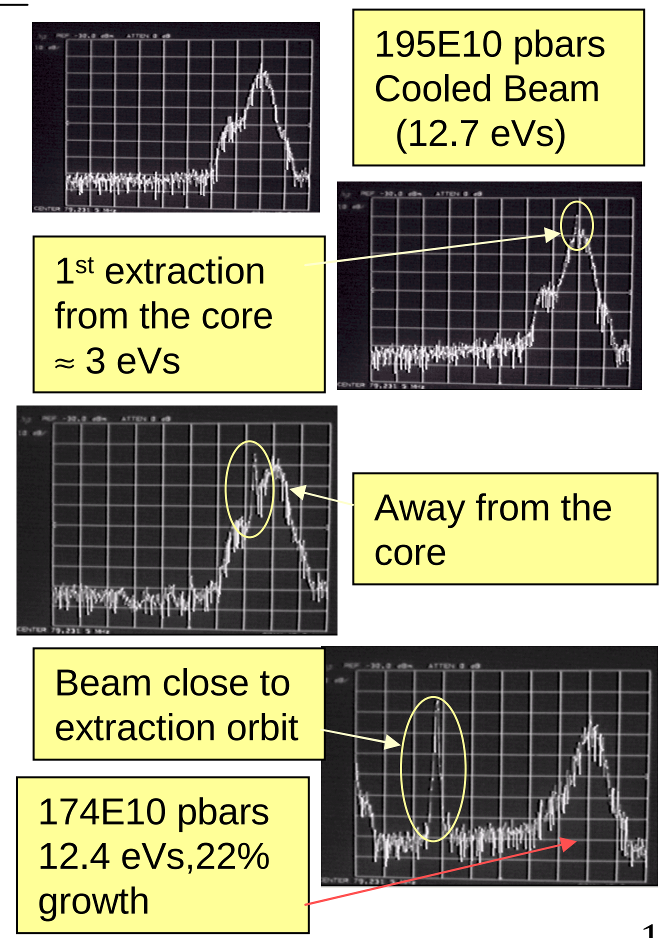
Transverse Momentum Mining

(Current Mining Scheme at the Fermilab Accumulator)





300% LE growth !!



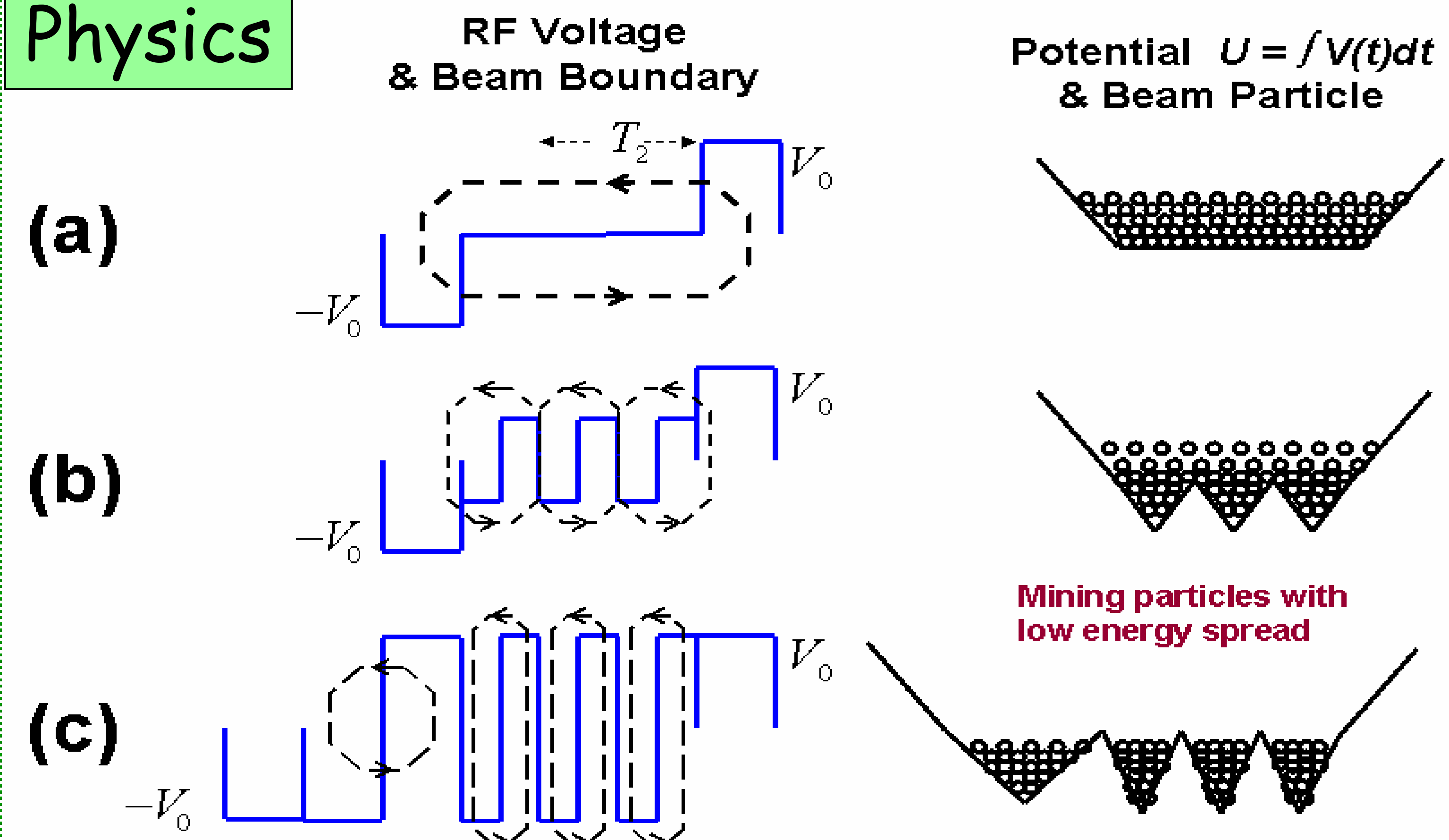
- This is the method used in all hadron storage rings so far.

Longitudinal Momentum Mining in a Synchrotron

New Technique

Ref: C. M. Bhat, Phys. Lett. A 330 (2004) 481

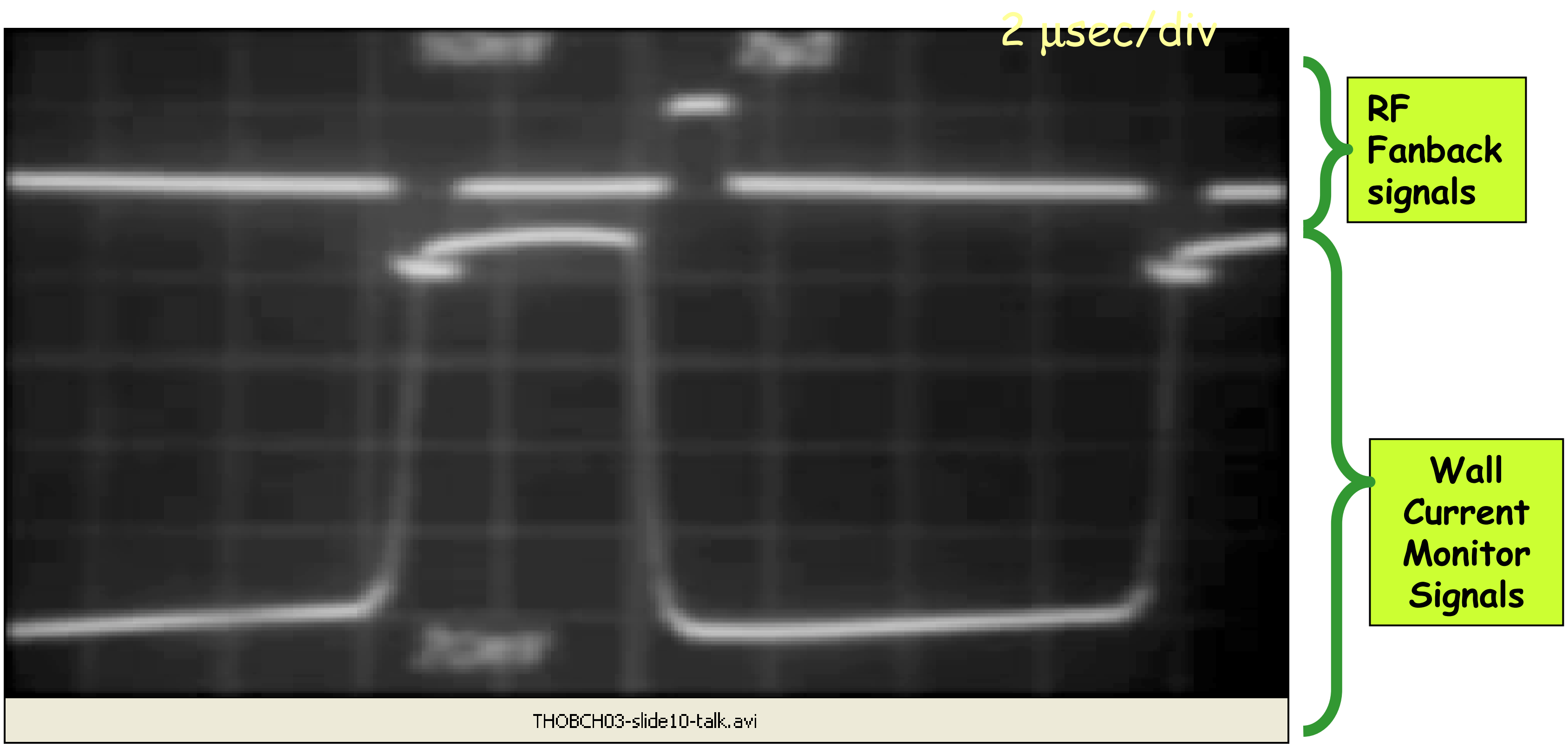
Physics



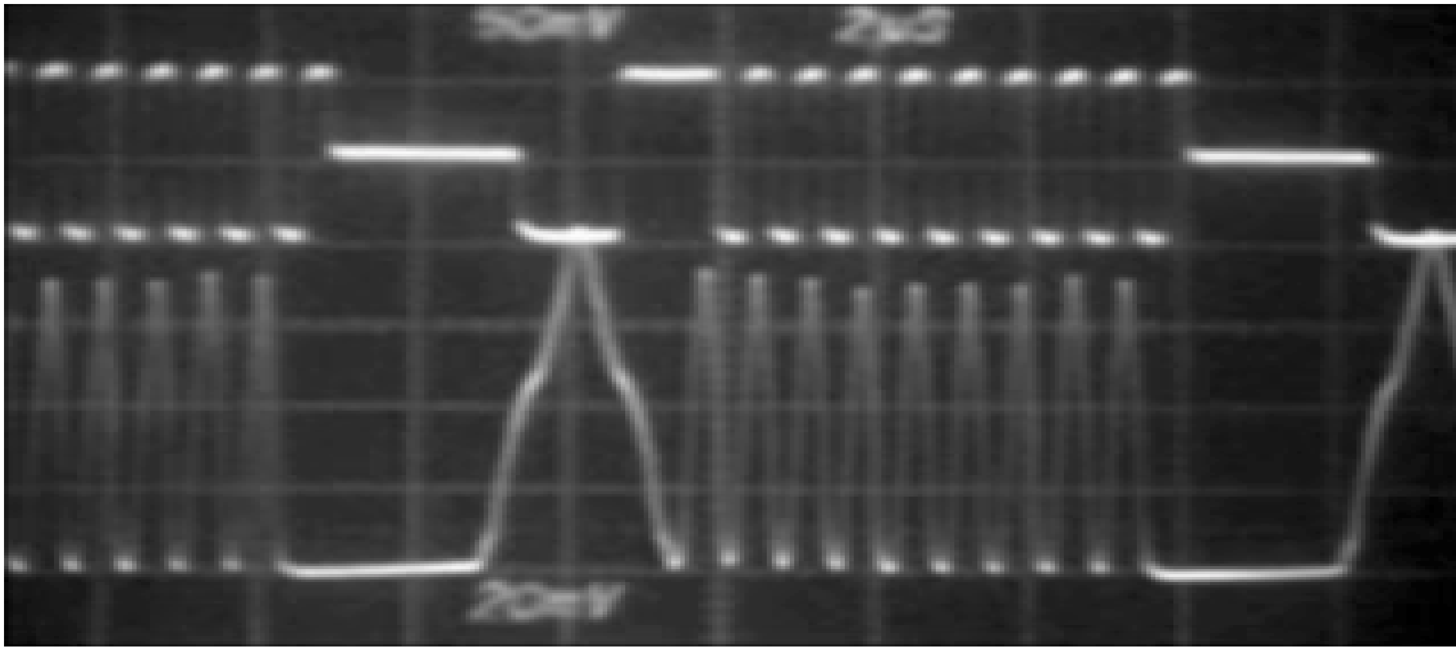
Technique is applicable to any storage ring for beam mining

Proton Momentum Mining in the Fermilab Recycler

(proof of principle)



Momentum Mining (cont.)
Tevatron Collider Shots



RF Fanback signals

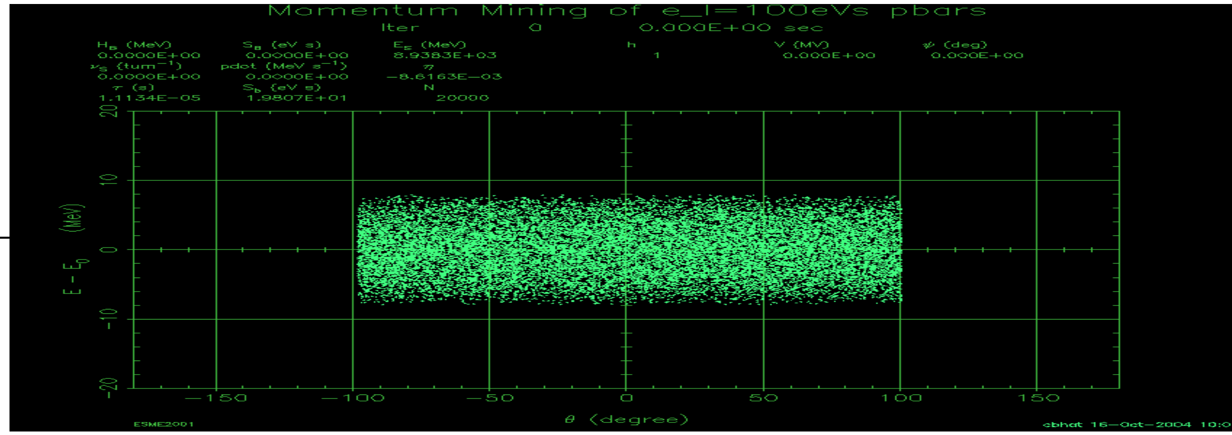
Wall Current Monitor Signals

We have successfully implemented longitudinal momentum mining in the Recycler to inject equal emittance, equal intensity pbars bunches for Tevatron shots.

<u>Outcome</u> –The **Longitudinal Momentum Mining** scheme is better than a factor of <2 more efficient than the "beam slicing scheme"

Pbar Momentum Mining at the Recycler (ESME simulations)

Phase-space Distribution of pbars

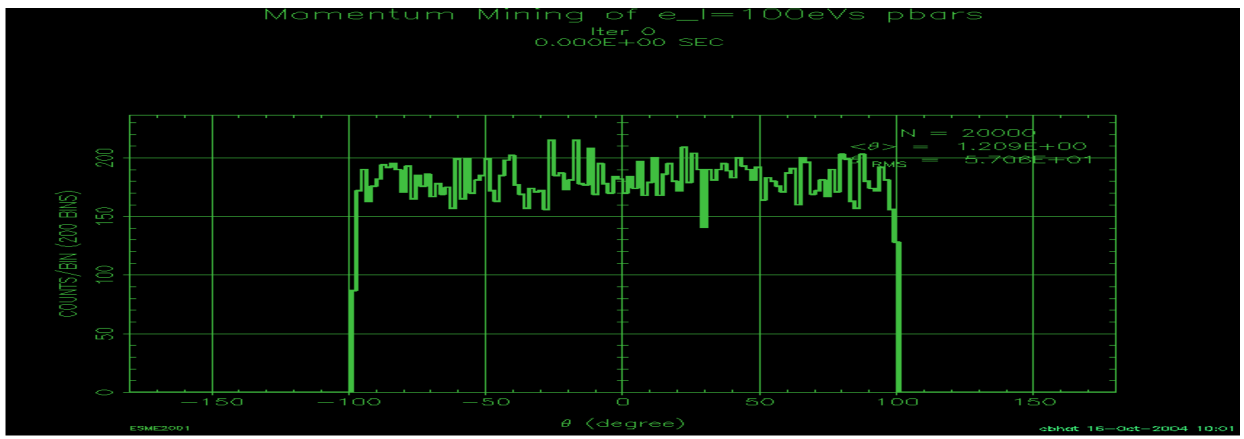


+ΔE

0

-ΔE

WCM data (predictions)



Intensity

Δθ (or Time)

360^0 (or 11.12 μsec)

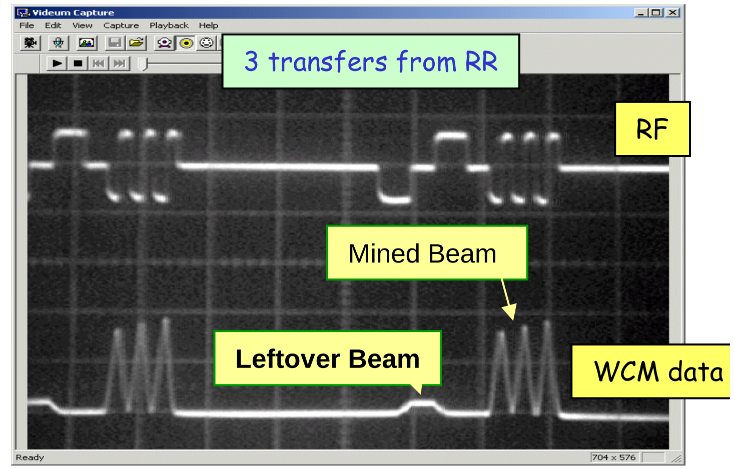
Recycler and the ppbar Luminosity

Mixed pbar shots

How can we get more pbars at collision $\Rightarrow$ Higher Luminosity

Solution: Use both Accumulator as well as Recycler pbars for the Tevatron shots ← Mixed pbar shots

- 6 Mixed Pbar Source Shots so far
  - 3 stores with Recycler supplying 3 of the 9 transfers to the Tevatron
  - 3 stores with Recycler supplying 2 of the 9 transfers to the Tevatron
  - Current Luminosity Record of $1.07 \times 10^{32} cm^{-2} s^{-1}$ (CDF/D0 Ave.)

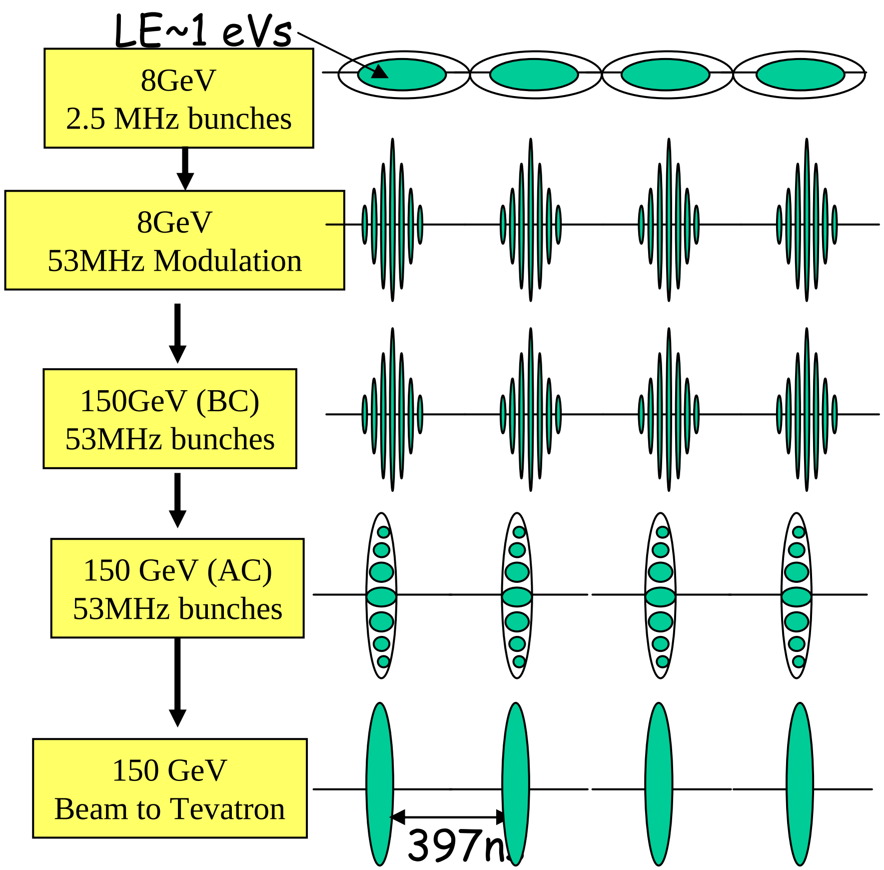


Top 4 Luminosity stores achieved is from Mixed Pbar Source Operation

Longitudinal Momentum Mining is crucial in the Recycler for the Tevatron shots

Bright pbar Bunches for Collider Operation

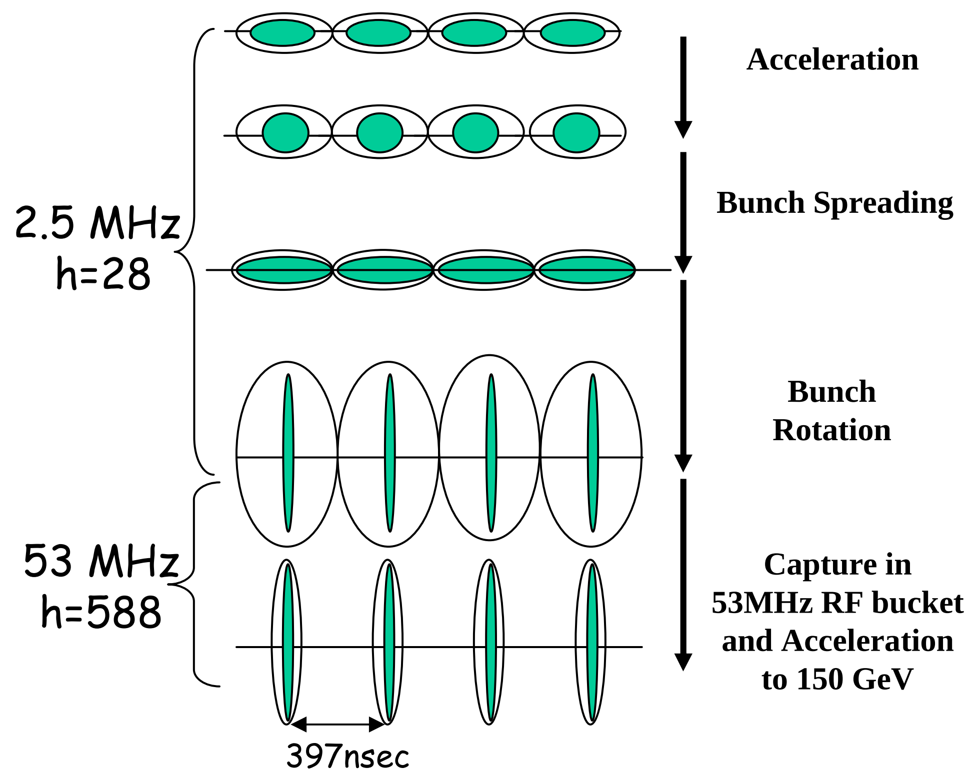
Current pbar Coalescing Scheme



>100% Longitudinal Emittance Growth and ≈10% pbar loss

New Scheme

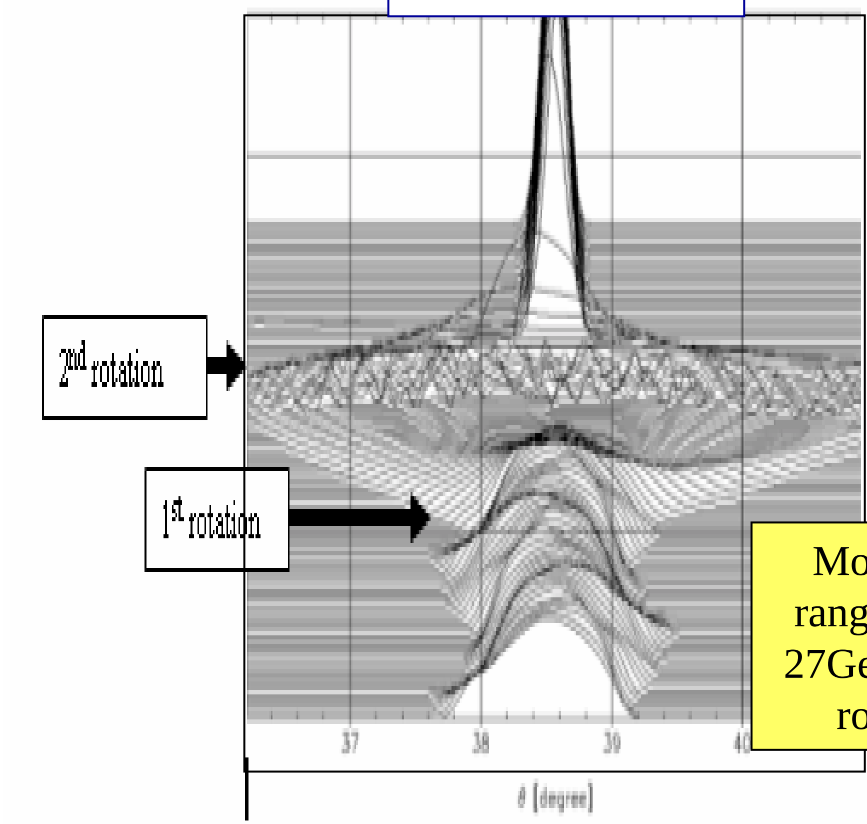
Harmonic Transfer



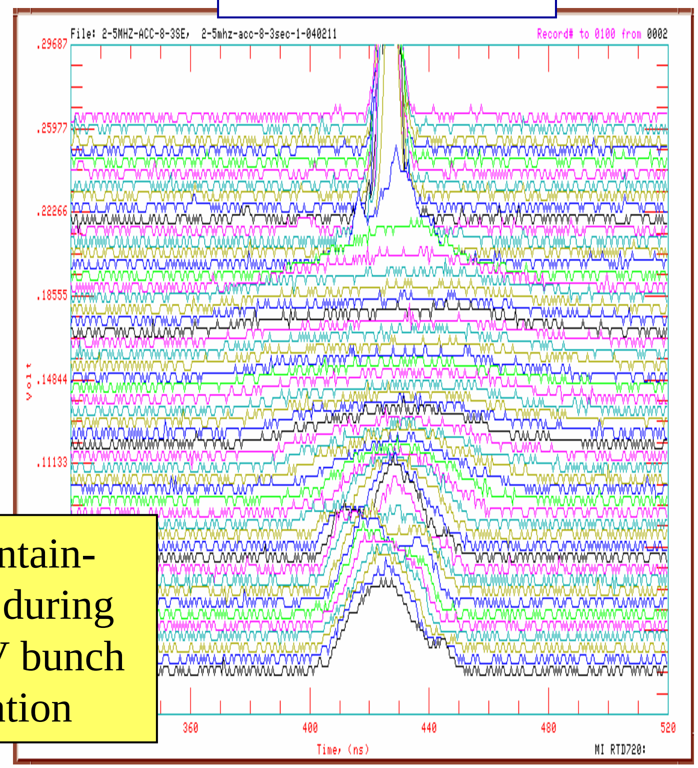
No Longitudinal Emittance Dilution, No beam loss

A comparison between Simulation Results and data during Harmonic Transfer

Simulations



WCM Data

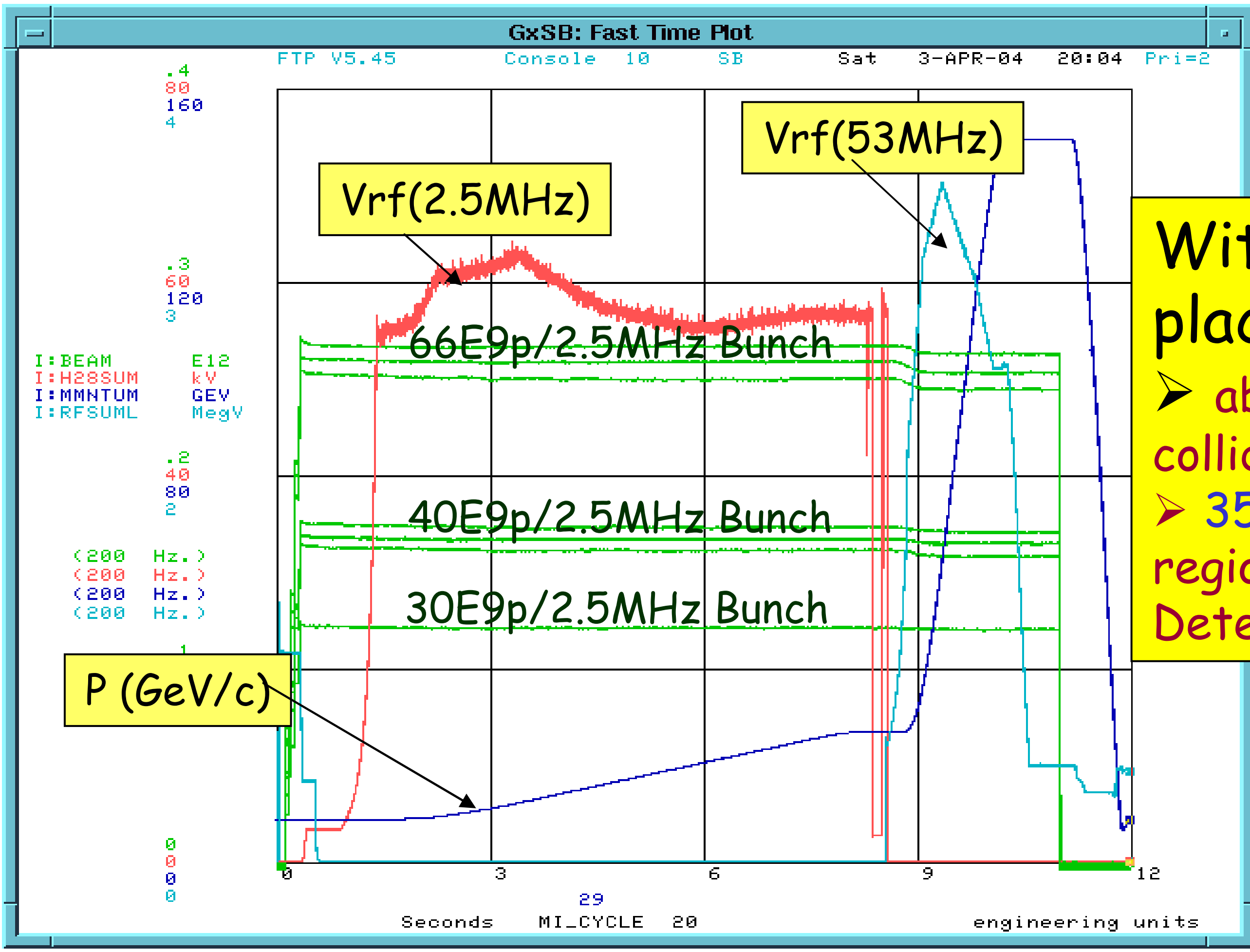


Mountain-range during 27GeV bunch rotation

For acceleration from 8-150 GeV

- <35% emittance dilution
- ~100% transmission efficiency

2.5MHz Acceleration in the MI

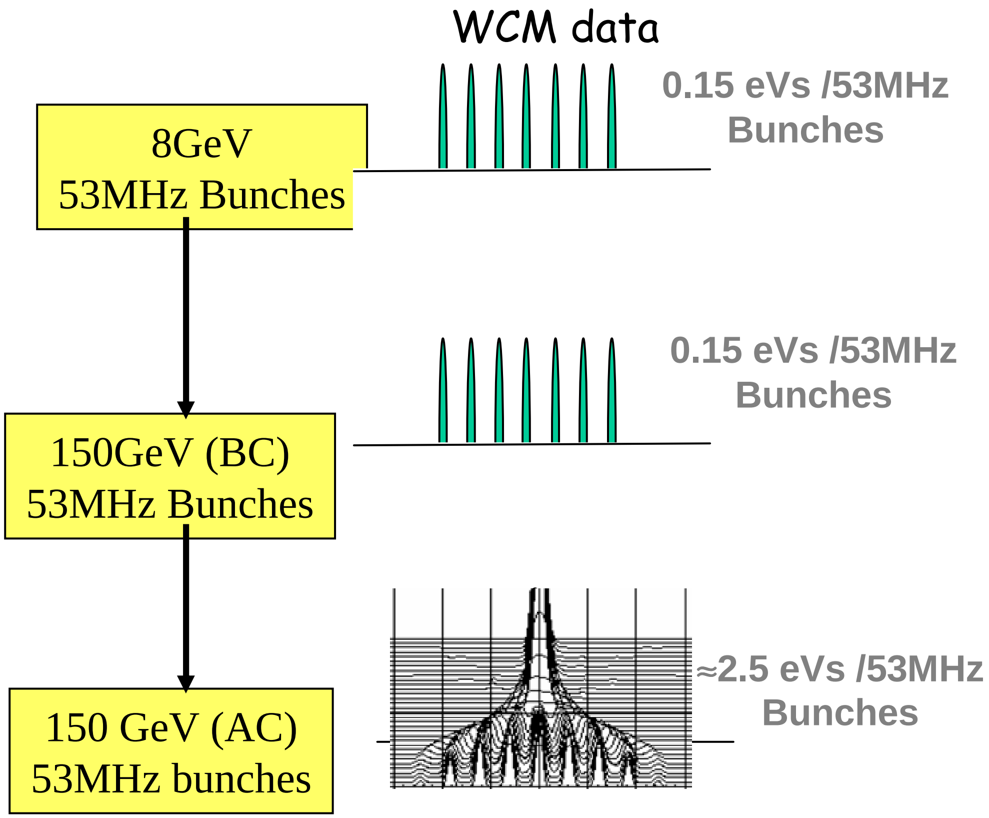


With this scheme in place one expects

- about 17% increase in collider luminosity
- 35% Shorter interaction region for the Collider Detectors

Bright Proton Bunches for Collider Shots

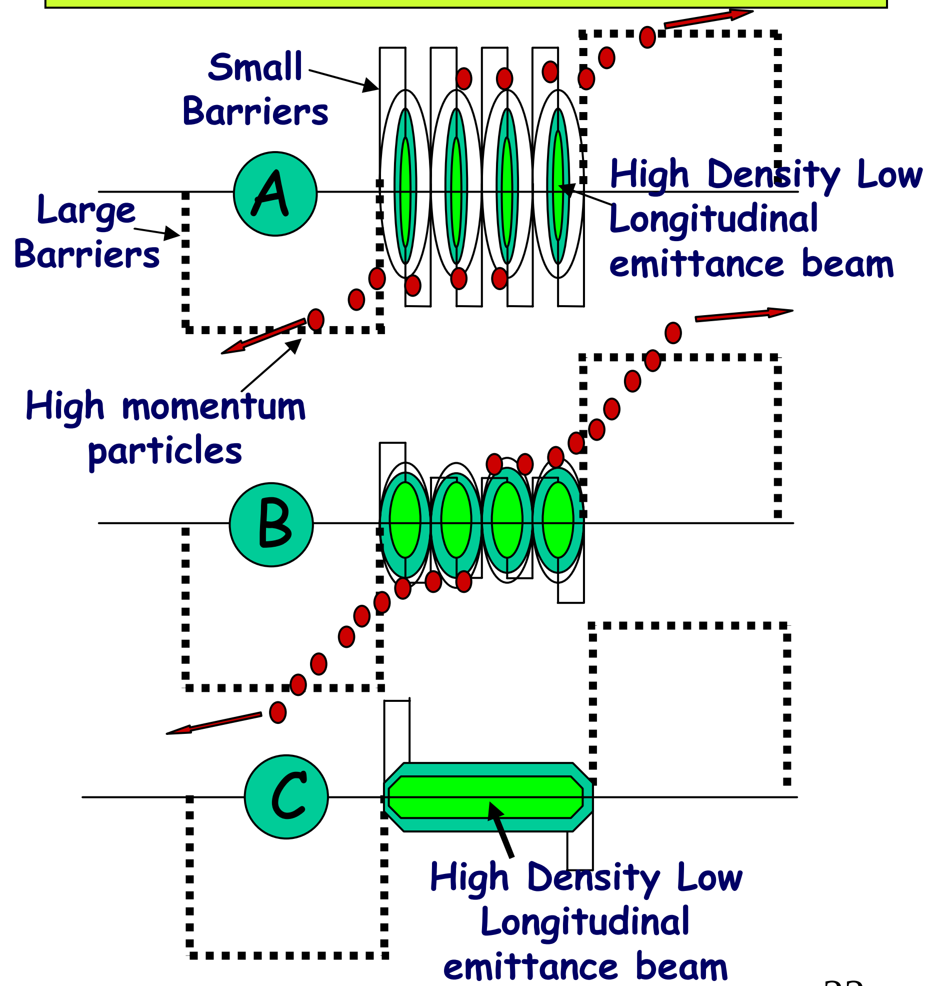
Current Bunch Coalescing Scheme



Longitudinal Emittance ≥2.5 eVs with <300E9protons/bunch

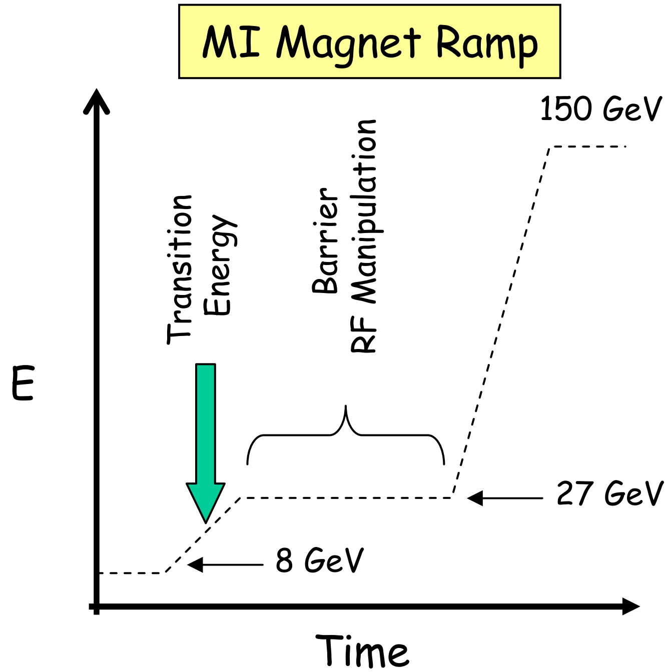
New Scheme: Barrier Coalescing

Ref: C. M. Bhat, FERMILAB-FN-0761-AD (October 2004)

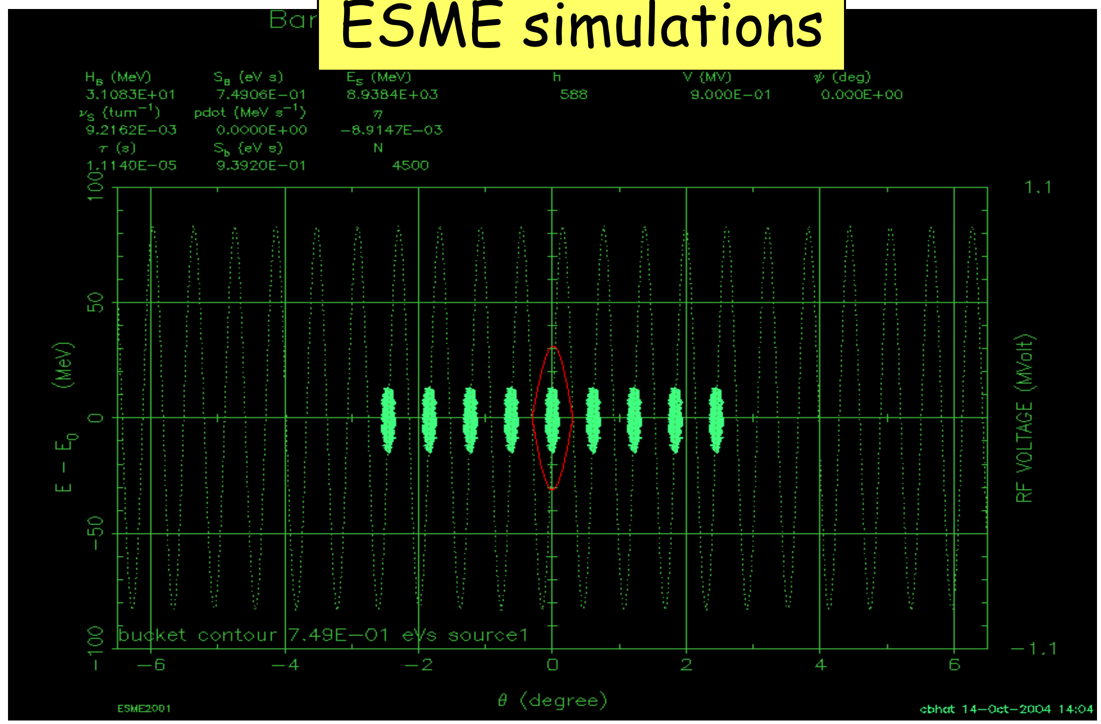


Bright Proton Bunches for Collider Shots

MI Barrier Coalescing



ESME simulations



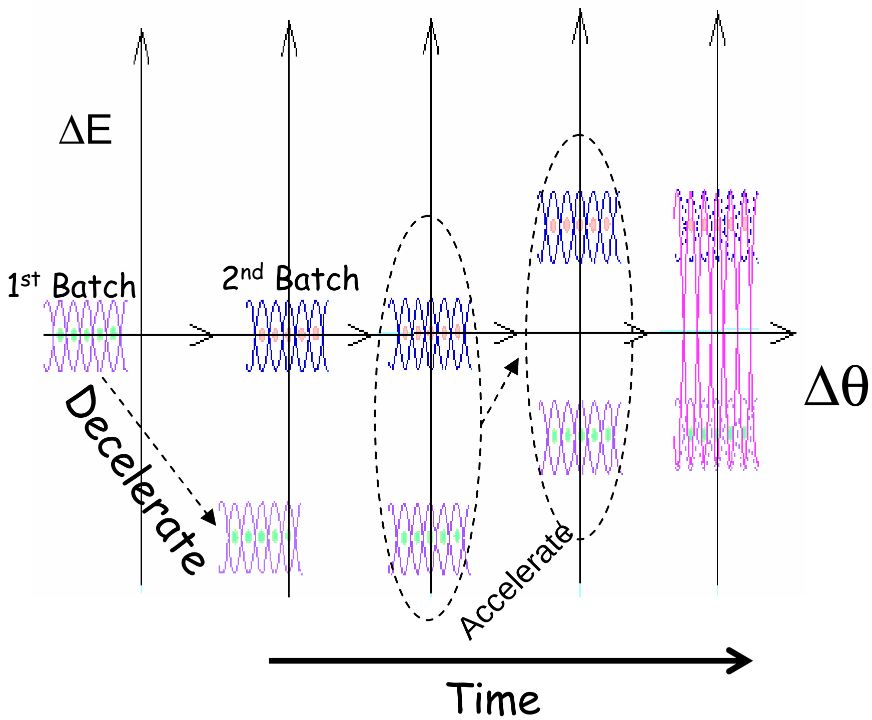
By this method one can send ~300E9 protons/1.5 eVs/ bunches for collider shots

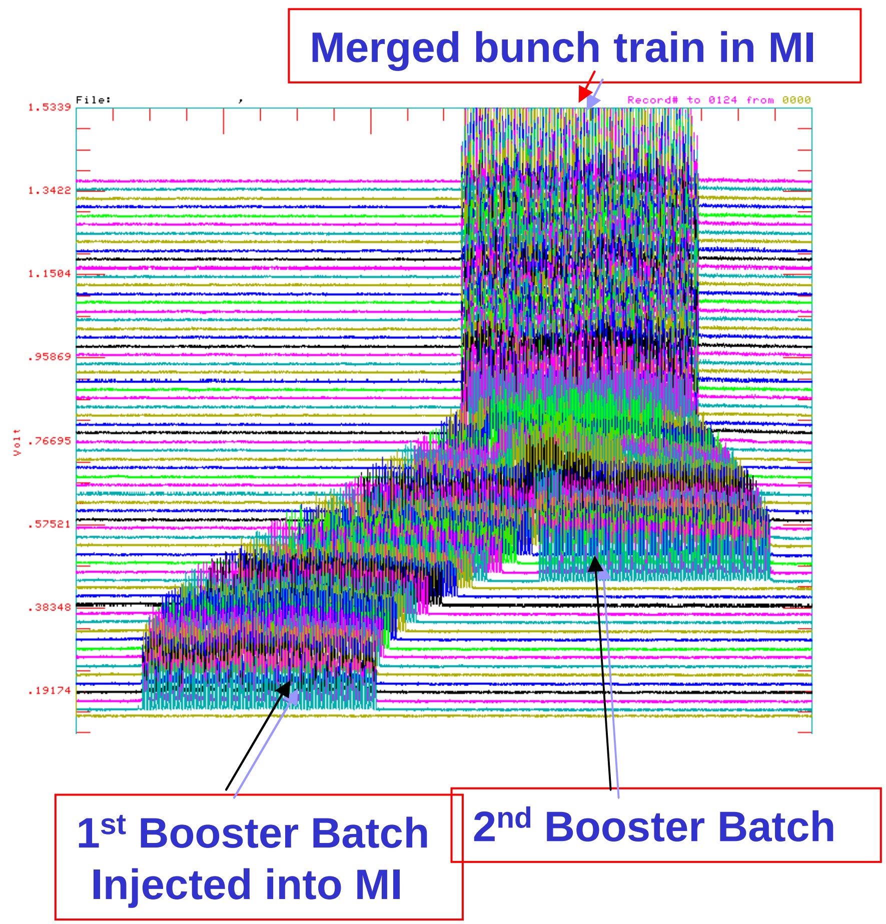
With this scheme one anticipates
- about 12-17% increase in collider luminosity

Protons on pbar Target

1. Slip Stacking (K. Koba et. al., PAC2003 page 1736)

- A scheme to merge two booster batches to double proton intensity on pbar production target





The protons on pbar target is up from 5.4E12 ppp to 7E12 ppp

With Slip stacking the pbar production rate has gone up by 15%

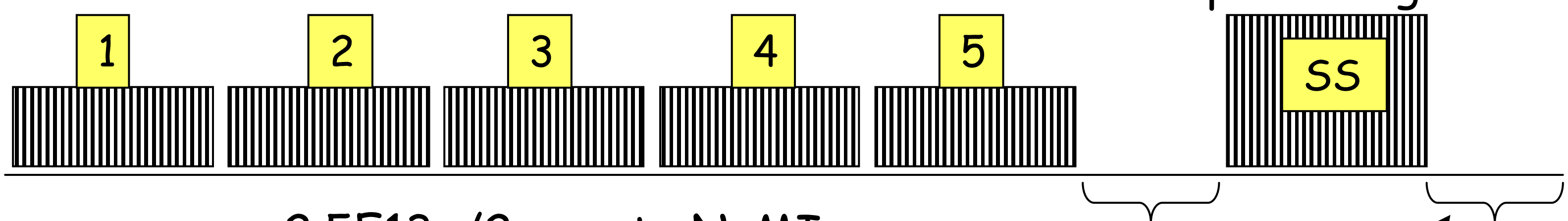
Slip-stacking and proton Beam for the Fixed Target Experiments

(Mixed Mode Operation)

Immediate Future:

Beam to Fixed Target Experiments
(NuMI and SY120)

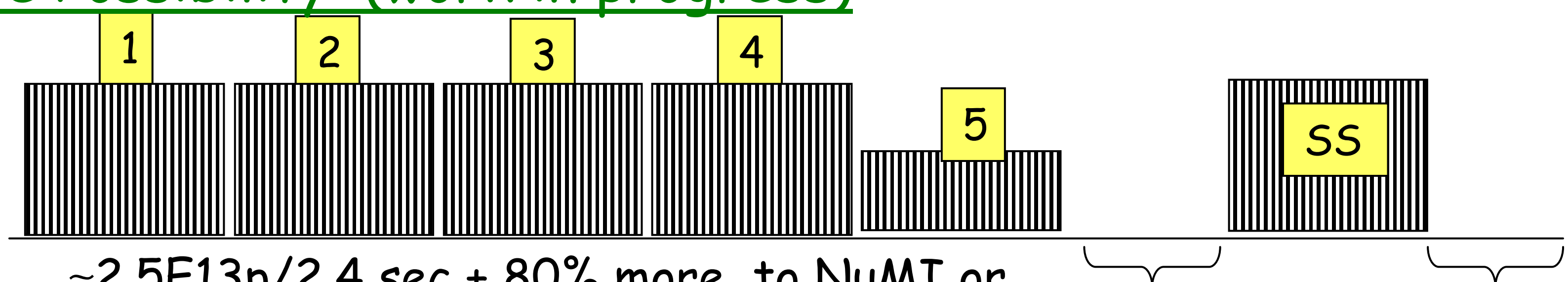
Beam to
pbar-target



≈2.5E13p/2 sec to NuMI or
≈2.5E13p/2.9sec to SY120

Kicker Gaps

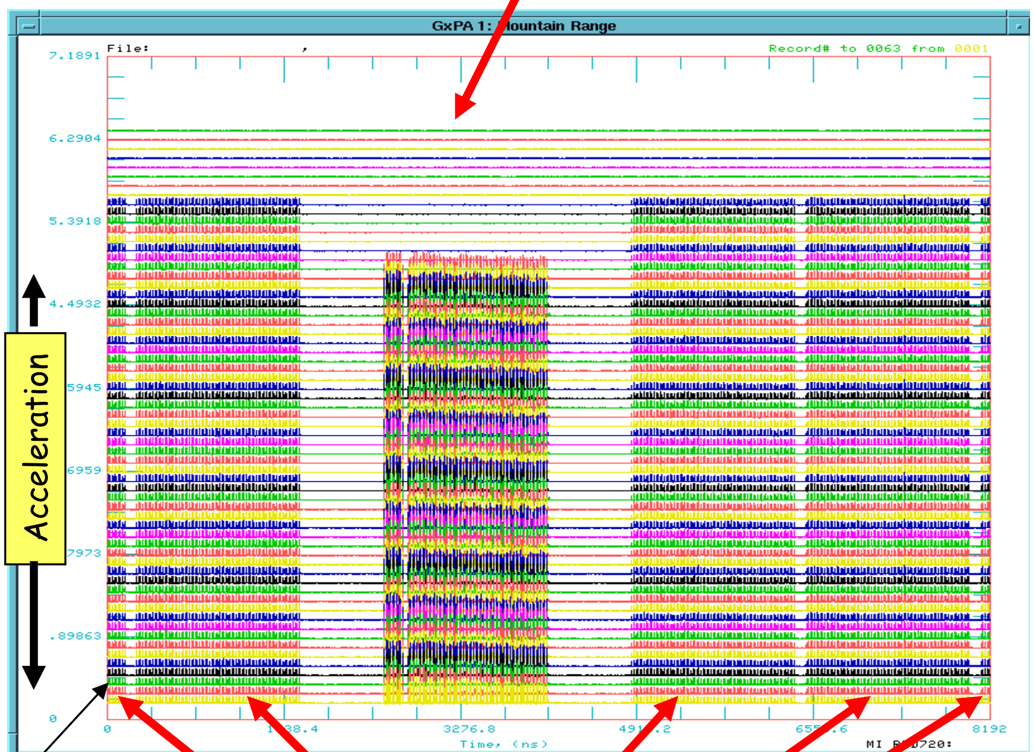
Future Possibility: (work in progress)



≈2.5E13p/2.4 sec + 80% more to NuMI or
≈2.5E13p/3.3 sec + 80% more to SY120

Demonstration of Mixed mode operation (NuMI multi-batch + Normal stacking)

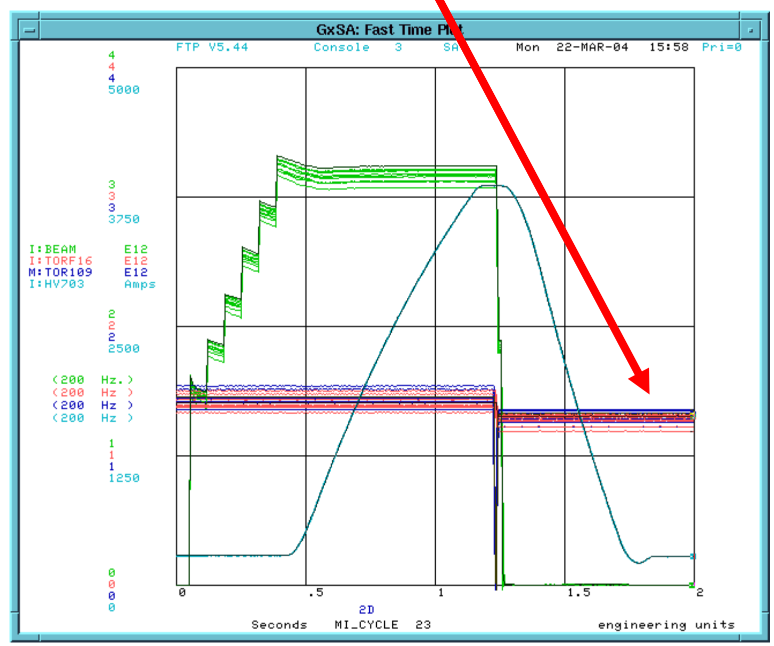
to pbar batch



Acceleration

Injection

Beam on the pbar target

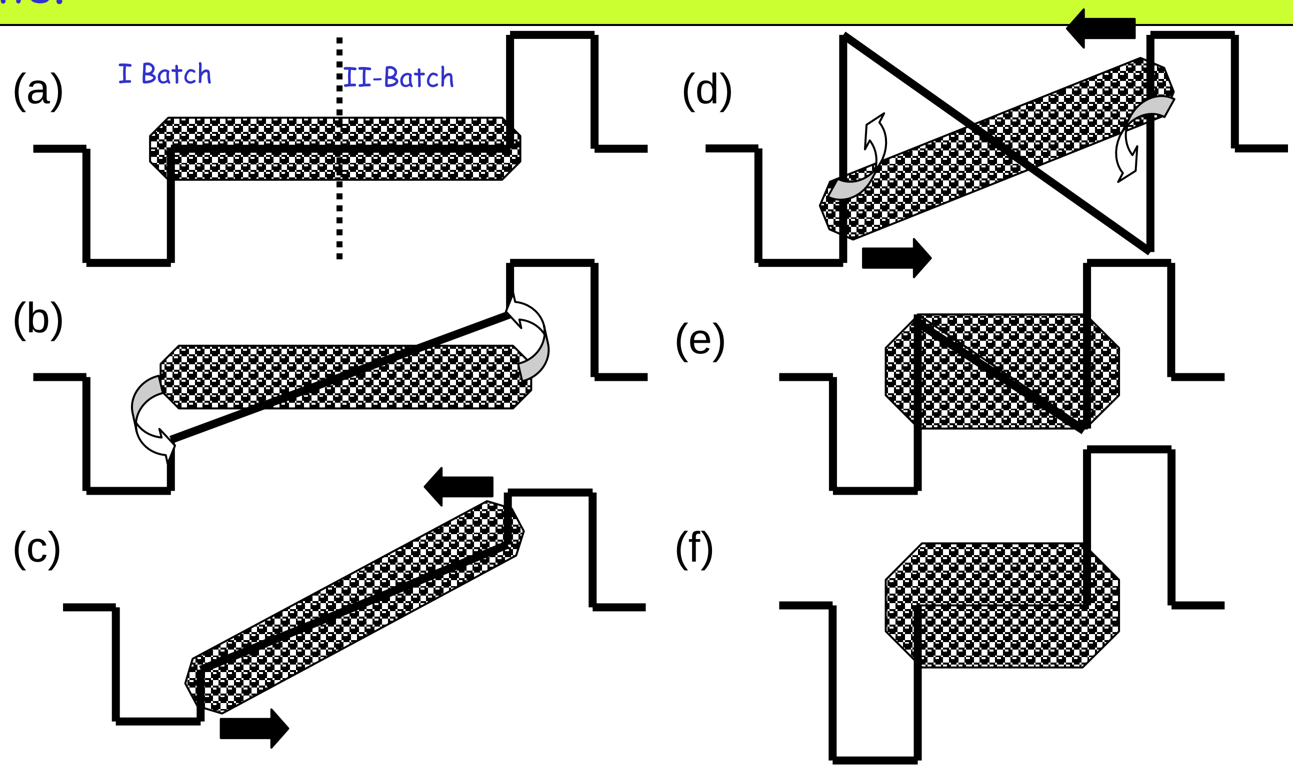


NuMI batches

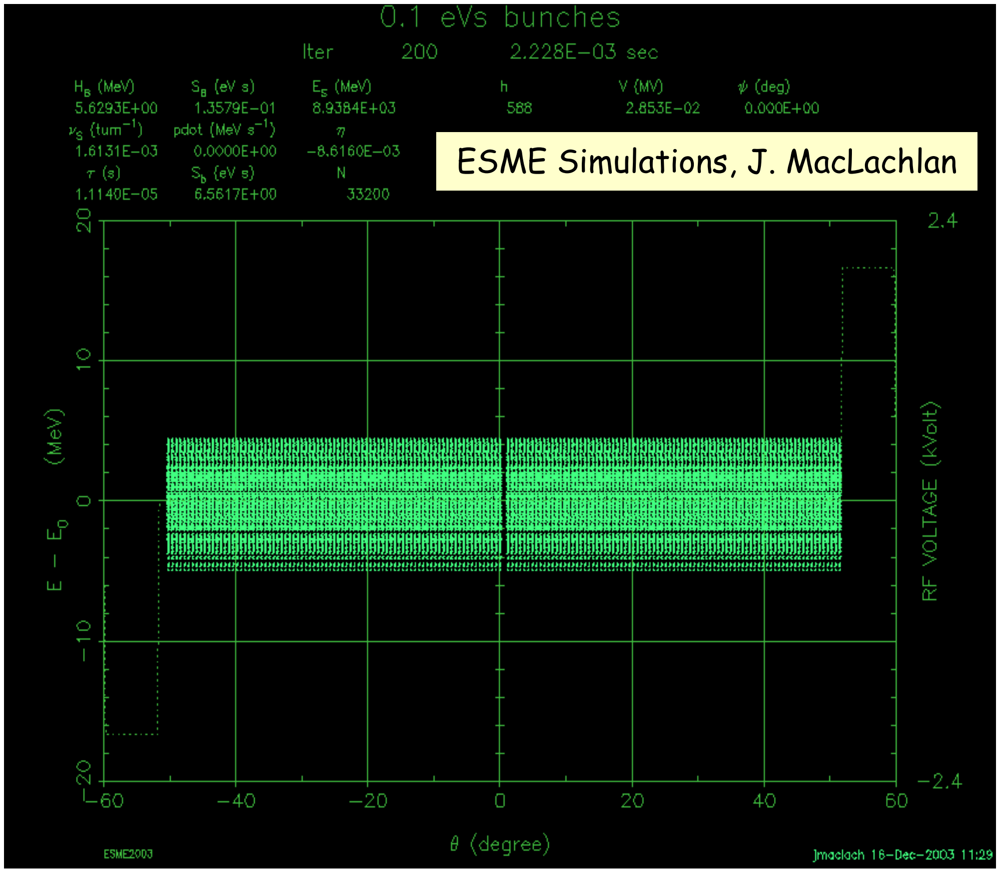
2. Flip-flop (G. W. Foster, C. M. Bhat, et al, Proc. EPAC2004, page 1479)

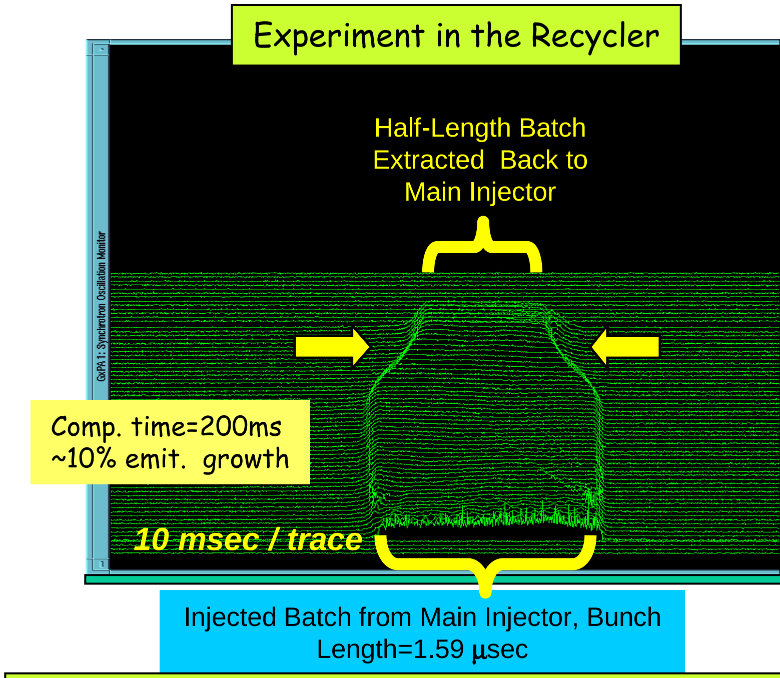
Beam for Antiproton production and Neutrino Experiments

Concept: Fast rotation of a bunch about rf stable and unstable points.



Flip-flop Technique: Simulations and Demonstration





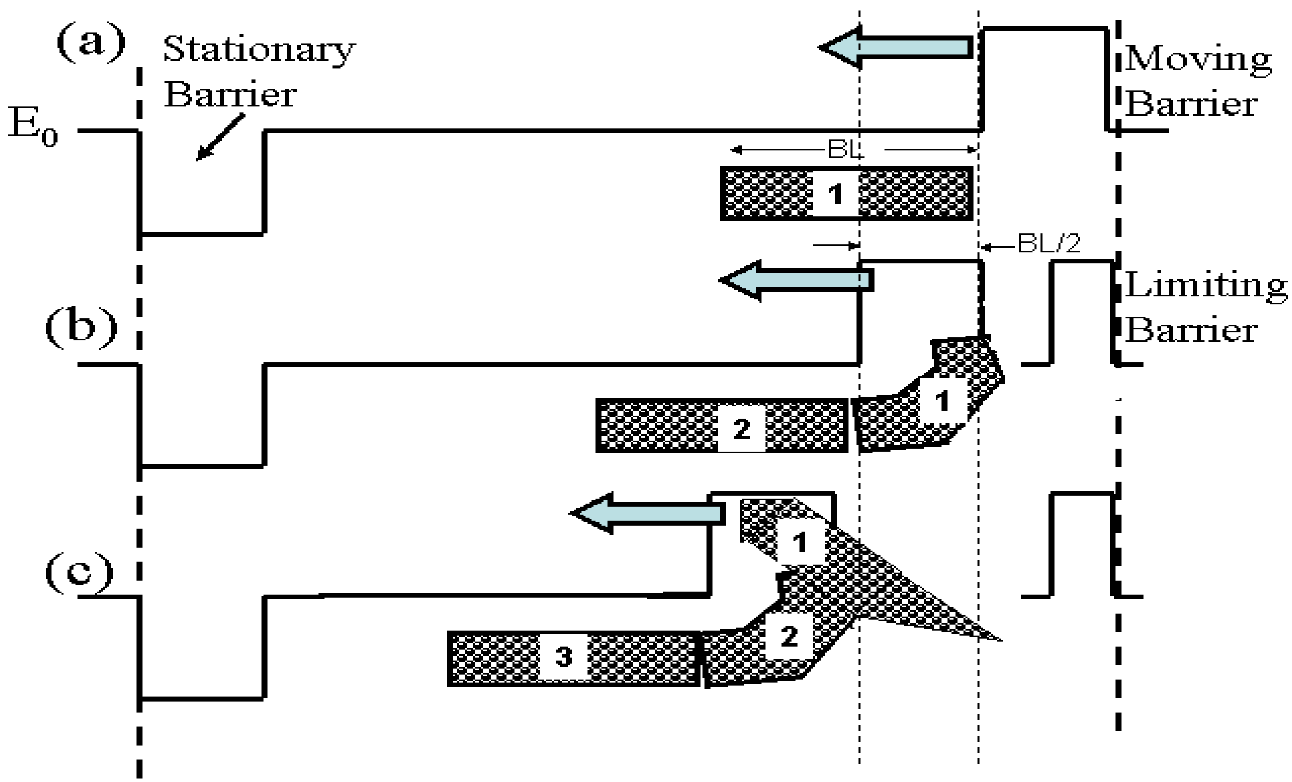
- With this scheme one can accelerate ~70% more protons to 120 GeV in the Fermilab Main Injector (Otherwise only 6 batches can be accelerated).

An experiment at the Fermilab Main Injector is in Progress using the newly installed barrier rf systems

3. Momentum Stacking

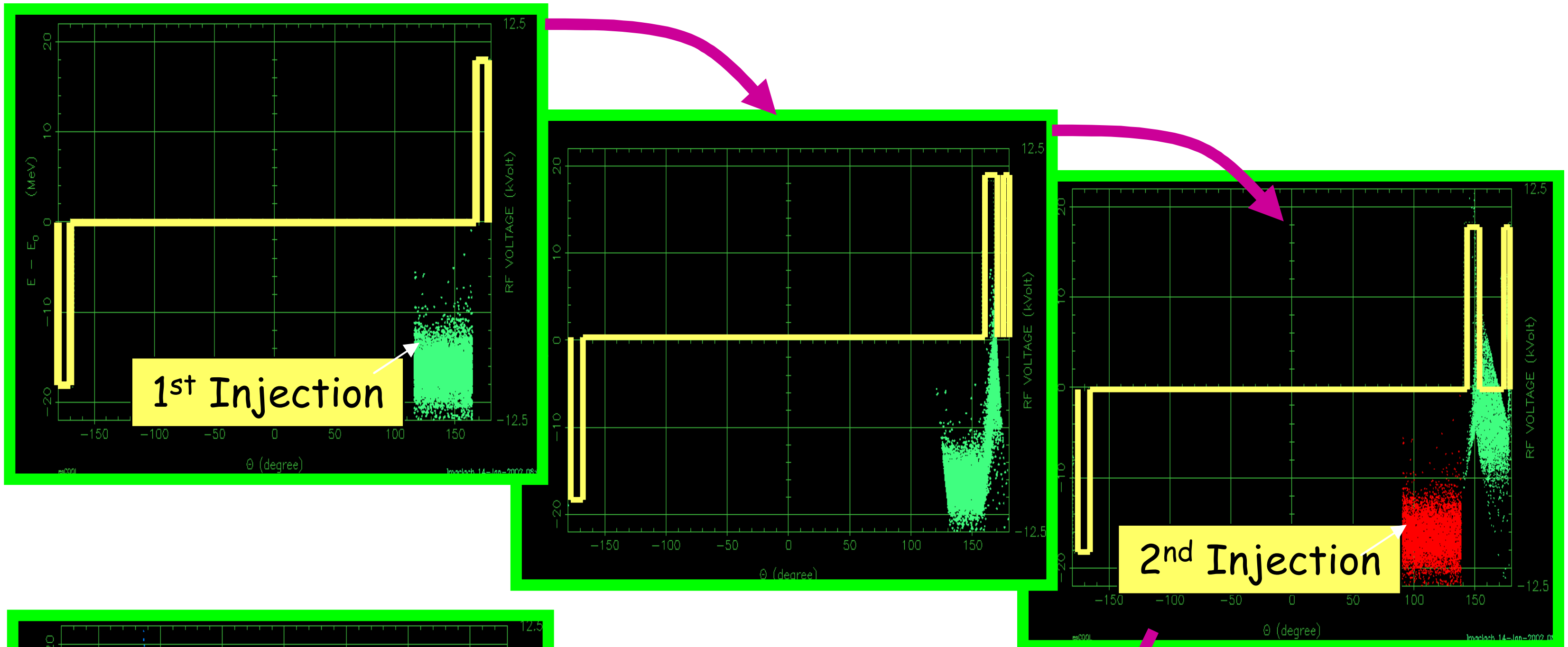
(J. Griffin-Private Communications & W. Chou et. al PAC2003, 2922)

Concept: Inject a Booster batch of protons slightly below the synchronous energy of MI between a stationary and a moving barrier pulse. Confine the beam batches in a limiting barrier. And so on.

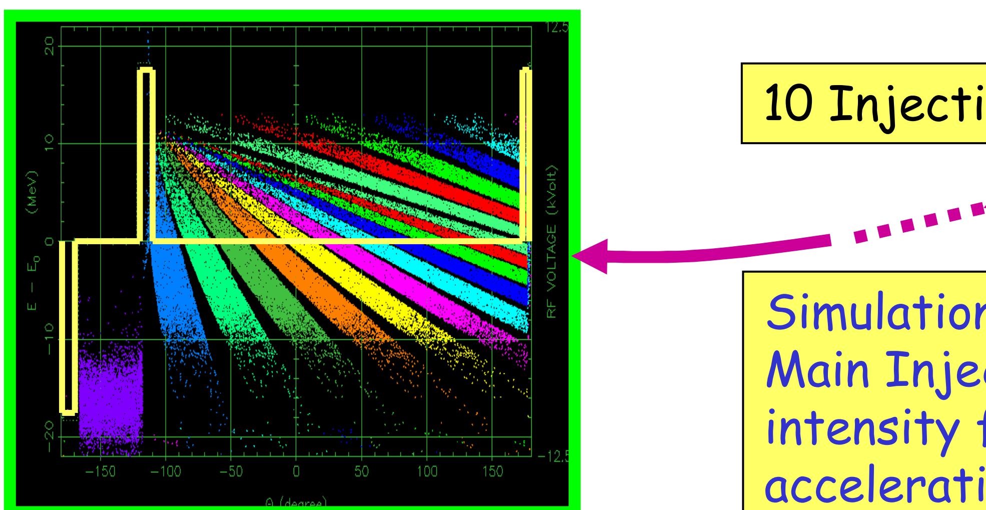


Barrier Stacking: ESME Simulations

(by Jim MacLachlan)



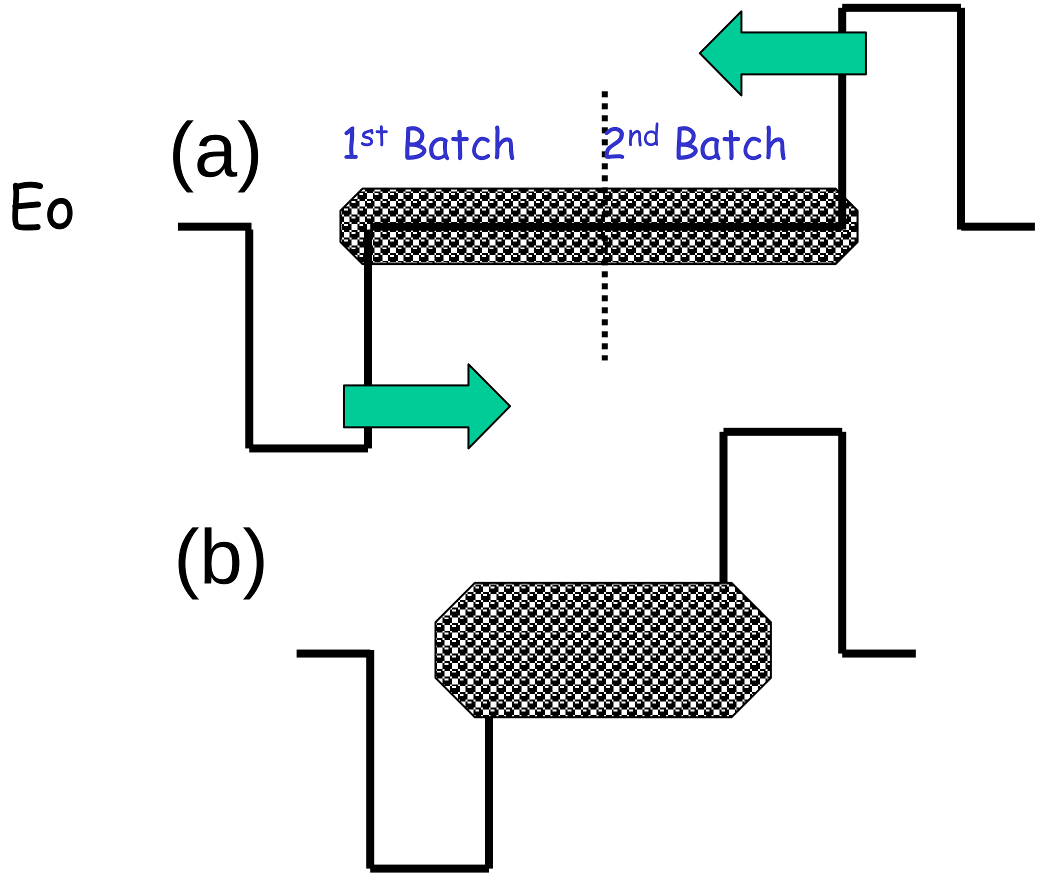
10 Injections



Simulations suggest that at the Fermilab Main Injector we can increase beam intensity from $\boxed{3\times10^{13}\text{ p to }6\times10^{13}\text{ p per}}$ acceleration cycle.

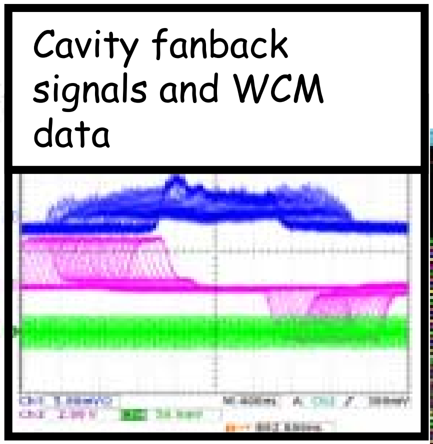
4. Adiabatic Compression

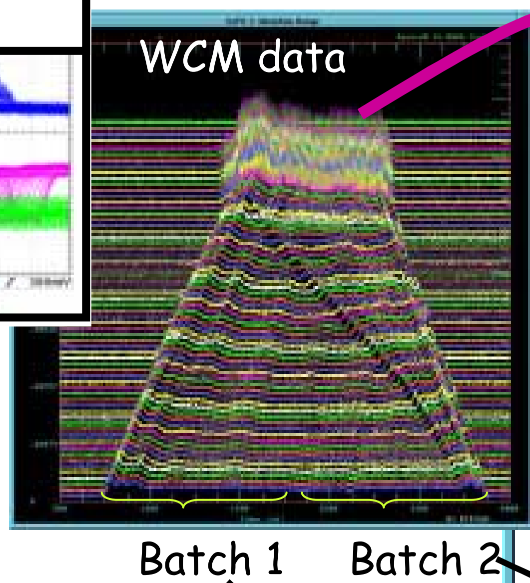
(D. Wildman, C. Bhat, W. Chou, et al.)

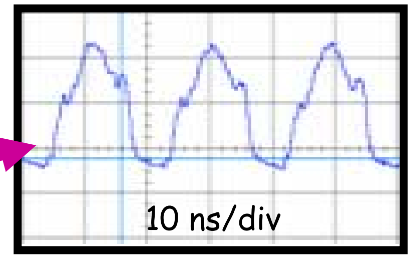


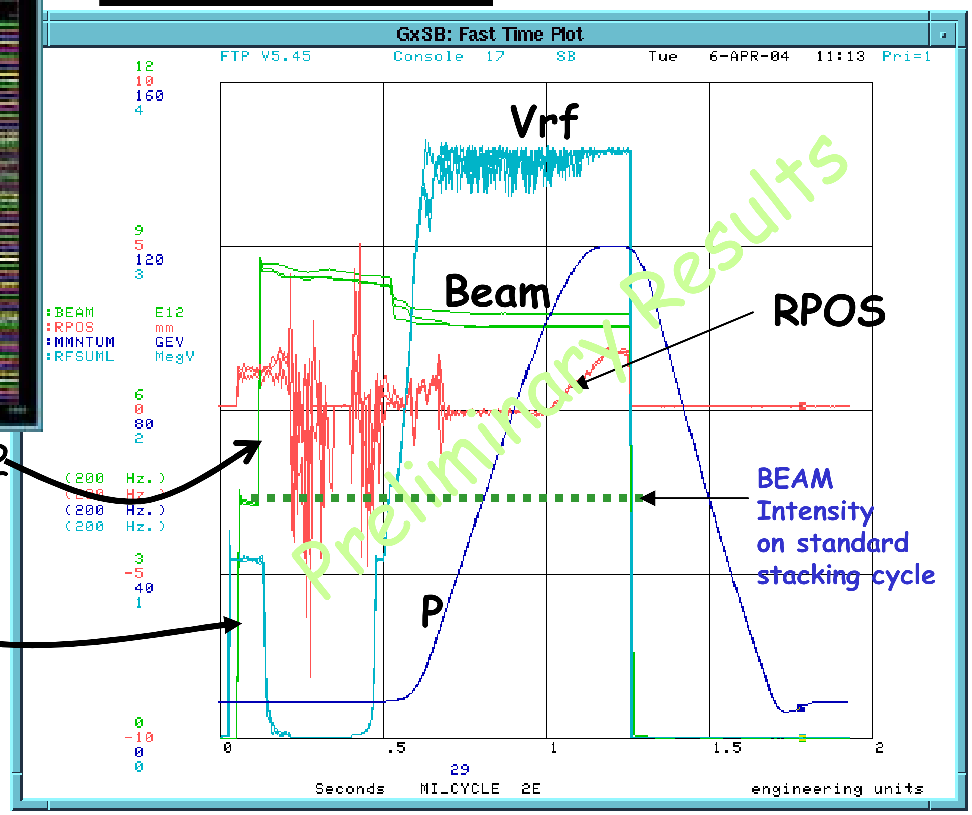
Concept: Inject two pulses of proton beam into a stationary barrier bucket at synchronous energy. Compress the beam adiabatically & symmetrically (or non-symmetrically) to half the original bucket size.

Experiment at the Fermilab Main Injector









Conclusions:

Have demonstrated acceleration of ~70% more beam than standard acceleration to 120 GeV.

Summary

- To support Run II and other programs at Fermilab, we have developed many Novel Beam Manipulation Techniques
  - Scheme called longitudinal momentum mining selectively isolates low longitudinal emittance anti-protons and is being successfully used for Tevatron shots from the Recycler.

    Has resulted in 20% increase in ppbar peak Luminosity
  - Successfully demonstrated harmonic transfer scheme for anti-proton acceleration in the MI. Is very important during Recycler era.
  - Slip stacking in MI has become operational and have seen ≈15% increase in anti-proton production rate. We are in the process of implementing for Fixed Target program.
  - New techniques based on barrier rf technology are being explored to help HEP programs.

Summary (Cont.)

- Fermilab has exciting opportunities in the Collider Program before LHC turns on
- Fermilab is shaping up to be a world-leader in Neutrino Physics program